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37th AIAA/ASME/SAE/ASEE JPC & E **(Statement A)**
(Salt Lake City, UT, 08-11 Jul 2001) (Deadline: 06 July 2001)

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AIAA 2001-3735

Solar Thermal Propulsion IHPRPT Demonstration Program Status

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37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit
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SOLAR THERMAL PROPULSION IHPRPT DEMONSTRATION PROGRAM STATUS

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ABSTRACT

This paper describes the final stages of a solar thermal propulsion ground-based test program funded under the IHPRPT initiative and sponsored by AFRL. A full-scale 4-by-6-meter off-axis parabolic concentrator and support system have been successfully built and deployed in both ambient and simulated space environments. The inflation control system has undergone improvements towards a flight-qualified design. The sun tracking and focus control systems have been successfully tested at the subsystem level. The integrated sun-tracking test stand is nearing completion. The engine has been designed and is in fabrication. The final program milestone will be a fully integrated on-sun ground test to demonstrate the fulfillment of the Phase I IHPRPT goals.

BACKGROUND

Solar Thermal Propulsion (STP) is an innovative concept that uses the sun's energy to heat a low molecular weight fuel such as hydrogen. The thermal energy stored in the hot fuel is then converted to kinetic energy by expansion through a diverging nozzle. This results in a high efficiency (800 – 1,000 sec Isp) low thrust (2-10 lbf) propulsion system[1]. Spacecraft propelled using STP systems have been proposed for orbital transfer, interplanetary, and other missions[2]. Other significant research for this approach has been previously performed and reported[3-9].

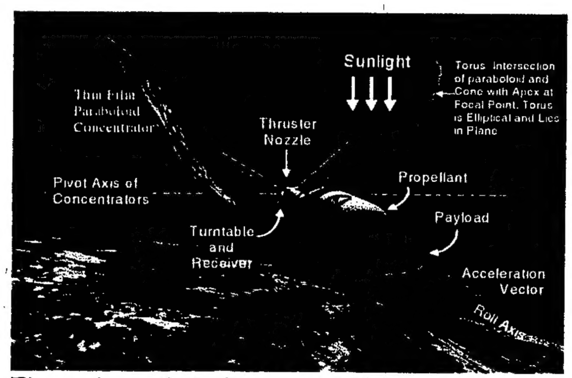

Figure 1. Artist's Concept of STP System

Figure 1 shows a conceptual view of a solar thermal rocket on orbit, featuring inflatable solar concentrators supported by inflated and rigidized struts. These concentrating mirrors are elliptical because geometrically they are actually opposing off-axis "slices" of a paraboloid whose axis points at the sun and whose focal point corresponds to the location of the

hydrogen engine.

Under Integrated High Payoff Rocket Propulsion Technology (IHPRPT) funding, The Air Force Research Lab (AFRL) has sponsored the team of ATK Thiokol Propulsion Corp. and SRS Technologies to demonstrate the technological readiness and performance of an inflatable solar thermal propulsion system. A previous paper[10] reported on last year's status of this program, including the following accomplishments:

- Component trade studies completed for struts, torus, lenticular
- Rapid prototyping and hardware-in-the-loop system installed and verified
- Inflation control system designed, fabricated, and tested in both ambient and space environments
- Conceptual design and 3-D dynamic model made of focus control system
- Sun sensors for focus control system fabricated and tested
- Subscale integrated system fabricated and deployed in space environment
- Modal testing of subscale inflatable concentrator completed in ambient conditions.

This paper describes the latest progress for the program in the following areas:

- Development, fabrication, and testing of a full-scale concentrator
- Improvements in the inflation control system
- Development and testing of the focus control system
- Sun tracking system testing
- Engine design and development
- Test stand design

The program will culminate in a full-up integrated proof-of-concept ground test later this year. This will demonstrate that the technology is ready for development of the flight hardware for the AFRL Solar Orbital Transfer Vehicle (SOTV) program.

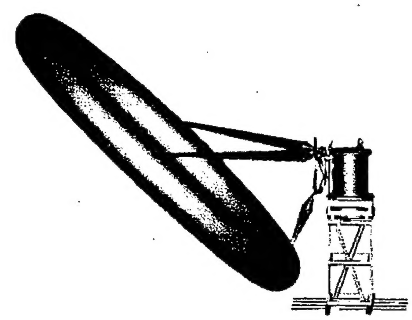

Figure 2. IHPRPT STP Demonstrator

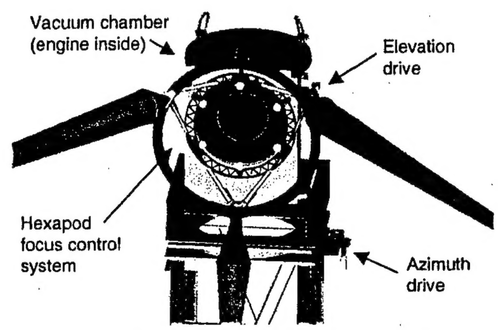

Figure 3. Close-Up of STP Demonstrator

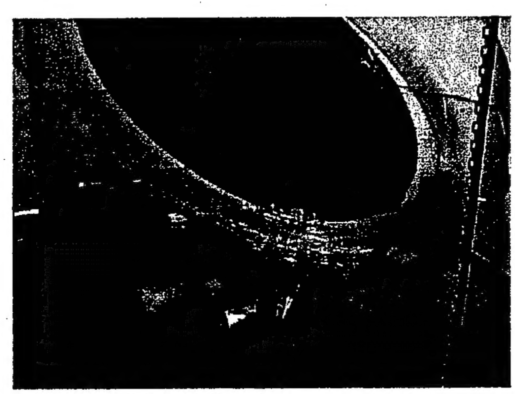

Figure 4. Thin-Film Concentrator Assembly During Integrated Test 4

INTRODUCTION

The IHPRPT STP Demonstrator consists of the following major components (Figures 2 and 3): 4-by-6-meter thin-film inflatable concentrator, inflation control system (ICS), sun tracking system (STS), focus control system (FCS), and direct-gain engine. These components are integrated together with a test stand. The following sections describe the development, fabrication, and testing of each of these components.

CONCENTRATOR DEVELOPMENT AND TESTING

The concentrator components (Figure 4) include a thin-film lenticular and canopy, a thin-film torus for support, a catenary system for attaching the torus to the lenticular/canopy, inflatable self-rigidizing struts, and a base ring for mounting. The struts are produced by ATK Thiokol Propulsion Corp. and are composed of an S-glass fabric tube impregnated with a UV-curable resin. A thin-film bladder inside the tube acts as the "mold" when it is inflated. After inflation in space, the resin cures in the natural UV environment, forming a stiff structural member. The torus and lens are made by SRS out of a NASA-developed film called CP-1, and require continuous low-pressure inflation in space. Research efforts are developing a rigidizable torus to increase mission life for operational systems.

Mandrel

One of the challenges has been the development of the 4-by-6-meter flight scale concentrator (FSC) mandrel, which is used for casting the CP-1 film into the precise concentrator shape. The high curing temperatures for CP-1 have historically led to the use of precision-machined metallic mandrels. The largest mandrel built to date has been a 5-meter diameter symmetric mandrel. Fabricating mandrels larger than 5 meters is very costly. Significant effort was made to develop a low-cost mandrel fabrication process. Several metals and technologies were considered, including stacked/welded plates, bump forging, and welded facets (tortoise shell). Each of these options required precision machining after assembly of the near-net blank. Vendors were found for each option, however, the material and fabrication costs were prohibitive.

To circumvent the need for a high temperature mandrel, a modified curing process was developed. The new process was a two-step cure made up of a low-temperature cure followed by a high temperature rapid cure. This made possible the use of lower cost materials for the mandrel, such as rigid foam. A prototype FSC mandrel was NC machined at NASA MSFC out of a large foam billet as shown in Figure 5. The foam mandrel was covered with a release material, and used to cast and cure the concentrator used for Integrated Tests 4 and 5 (IT-4, IT-5), which are described below. Process improvements were developed to improve the film quality, and another concentrator was cast and cured for optical evaluation during the upcoming IT-6 test.

Another low cost mandrel concept currently being developed uses a near-net machined foam mandrel as a lay-up tool for building a composite mandrel. The composite mandrel is comprised of fiberglass and an innovative new liquid tool paste product. The initial fabrication process of the tool paste mandrel was not successful due to material handling and curing problems; however, process improvements are being finalized and initial results appear very promising. A sub-scale elliptical concentrator is currently being fabricated using the machined foam mandrel and the same casting/curing techniques used for the FSC concentrator. The elliptical concentrator will also be tested during IT-6. Figure 6 shows the cured fiberglass shell covered with the tool paste prior to final machining.

Integrated Test #4 (IT-4)

The purpose of the test series IT-4 was to quantify the variation in deployed global geometry for multiple deployments of the first flight-scale concentrator known as FSC-1. A second objective was to verify that the new lightweight ICS would function properly for a 4 X 6 meter concentrator.

FSC-1 was the first concentrator made using

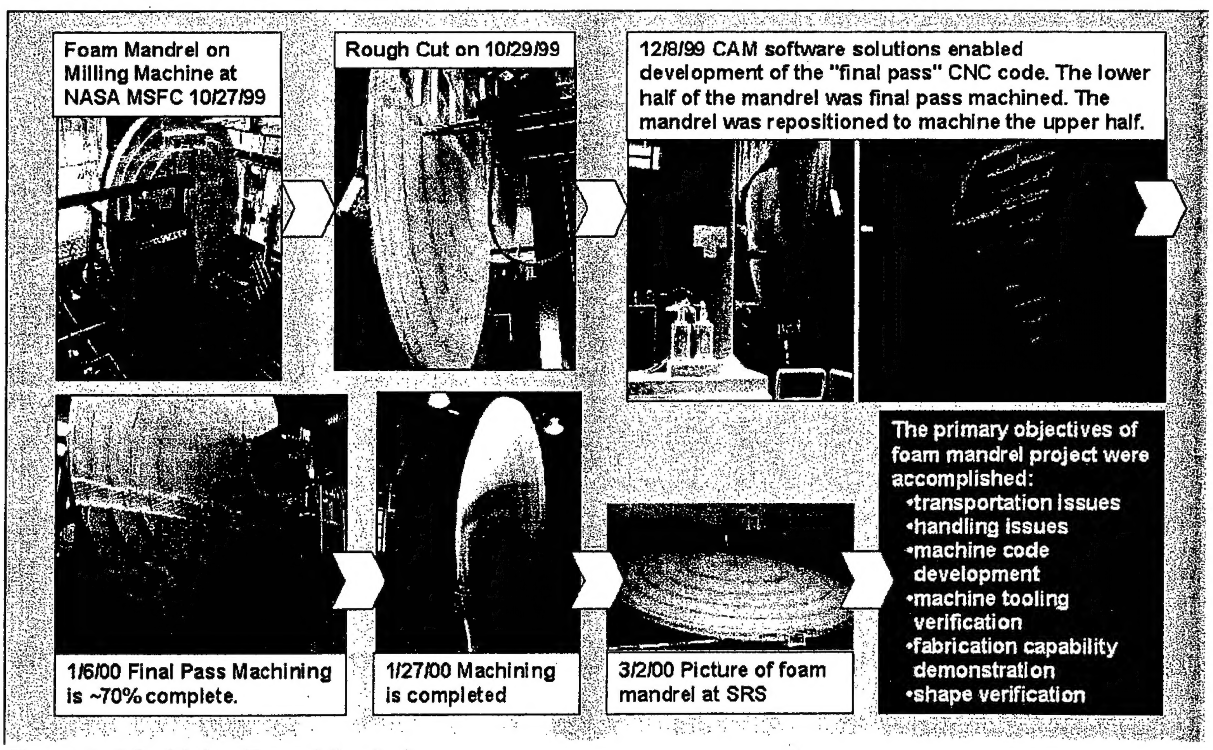

Figure 5. Machining Foam Mandrel

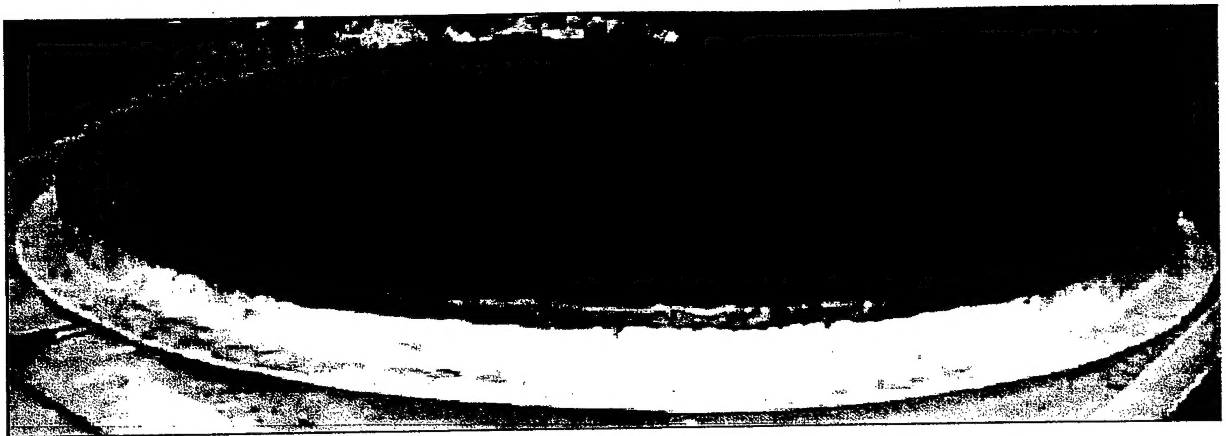

Figure 6. Composite Mandrel

the foam mandrel casting process. Figure 7 shows some steps in the assembly process, and Figure 8 illustrates initial on-sun testing. Due to some processing difficulties, it was not of one-piece construction, but was seamed with tape, which distorted the optical quality. However, it was still adequate for demonstrating deployment and global geometry of the structure.

During the initial test setup, the struts were inflated, adjusted to the drawing dimensions, and interfaced to the inflated torus (see Figure 4). Several folding patterns were tried. It was discovered that the weight of the concentrator in the 1-G environment prevented the strut ends from unbuckling and fully deploying. Helium-filled bags were used to off-load the strut ends. This would not be a problem in the low gravity of space.

Four tests of deployment and geometry characterization were conducted. Digital photogrammetry (DP) was used to measure the geometry of the structure, especially the strut ends. The global geometric coordinates for the DP targets on the strut ends were compared. The greatest target standard deviation observed was 0.4 inches for the end of the right strut. All strut deployment variations observed were well within the capability of the focus control system to correct.

The inflation control system (see section below) performed flawlessly. While its low flow capacity results in long inflation times for ambient deployment of flight-scale concentrators, no problems are anticipated for vacuum deployments.

Integrated Test #5 (IT-5)

The purpose of IT-5 was to deploy FSC-1 in both ambient and simulated space environments and quantify the effects on the global geometry. A second objective was to verify that the new lightweight ICS would function properly for a 4 X 6 meter concentrator in the space simulated environment. These tests were conducted in the Air Force Research Laboratories (AFRL) Space Environmental Test Facility (SPEF) (see Figure 9).

The integrated concentrator system including the concentrator, support torus, struts and ring were packaged into a container about the size of a large suitcase mounted to the inside of the SPEF chamber lid (Figure 10). Two deployments were performed. First, the concentrator was deployed at ambient pressure inside the chamber to verify clearances. A solid model of the deployed concentrator in the SPEF was used to define the precise mounting location and orientation in

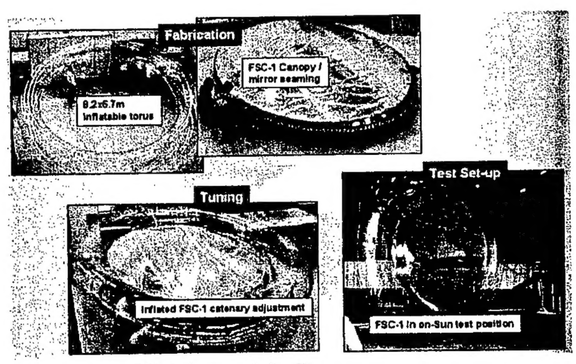

Figure 7. FSC Assembly Process

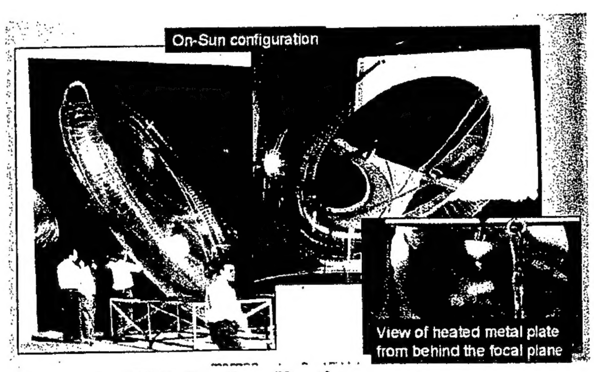

Figure 8. FSC On-Sun Testing

the lid. The resulting maximum clearance was about 3". Low power helium-neon laser pointers were then installed and aligned. Two laser pointers were mounted to the chamber wall approximately 80 degrees apart and pointed at a 0.25-inch grid on each strut end. Still photos from a video camera were used to document strut movements.

Next, the concentrator and struts were deployed inside the SPEF during a 30 minute controlled deployment sequence (Figure 11). The SPEF chamber was evacuated to a pressure of less than 6.0 x 10–6 torr. Deployment was accomplished by cutting the containment cover strap with a resistive hot wire. The ICS then successfully completed a slow controlled inflation of the struts and torus over 12 minutes. Next, the lenticular was slowly inflated over 20 minutes. The composite struts deployed in an uncured state and were cured (rigidized) by UV radiation during the deployment test.

The difference in measured deployment geometry of the strut ends was within one-half inch between the two tests. Also, no movement of the cured struts was observed when the inflation pressure was released. The test successfully demonstrated the controlled deployment of a 4x6 meter off-axis membrane concentrator system in a vacuum environment.

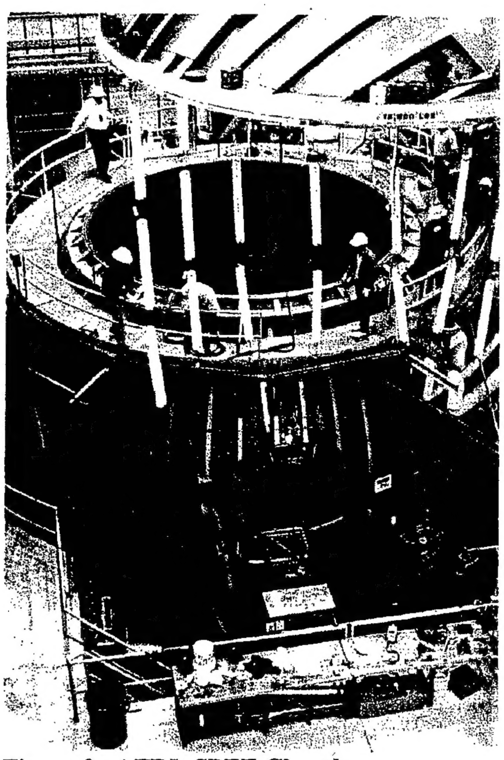

Figure 9. AFRL SPEF Chamber

Figure 10. Pre-deployed Concentrator

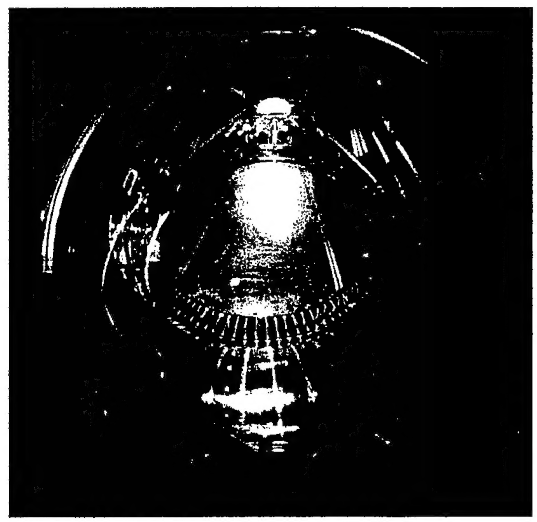

Figure 11. Deployed Concentrator

INFLATION CONTROL SYSTEM (ICS)

The development of the ICS was documented in detail in a previous paper[11]. Important progress was made in replacing heavyweight components with flightweight. Figure 12 shows the new valve manifold mounted to the bottom of the support ring shield, and Figure 13 shows the new torus and lenticular fill/vent valves. The new ICS functioned well during the ambient deployments in IT-4 and IT-5. The vacuum deployment of IT-5 revealed that the valves were leaking and preventing controlled deployment. The old ICS was then used during the vacuum test. Efforts are continuing to find adequate flightweight components. Valves based on MEMS technology are being considered.

SUN TRACKING SYSTEM

The sun tracking system is an integral part of the test stand, essentially enabling the stand to track the sun in both azimuth and elevation directions. The drive systems feature Smartmotors from Animatics Corp. that provide rotation using timing belts and bearings. Key

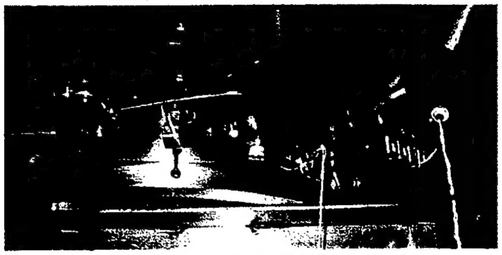

Figure 12. Flightweight ICS

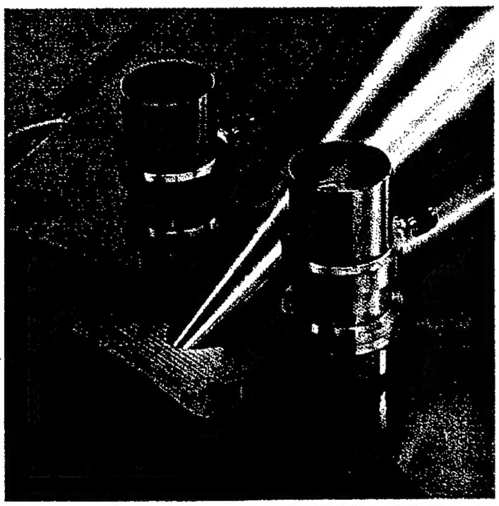

Figure 13. Concentrator Fill/Vent Valves

components of the closed-loop control are the 2 sun sensors manufactured by the Space Dynamics Laboratory of Utah State University.

A previous paper reported on the design and acceptance testing of the sun sensors[10]. The latest accomplishment is the creation of the code to enable the AC104 controller (from Wind River) to read the data from the sun sensors. Each sun sensor detects the angle between itself and the sun (light source). This angle, once detected, is held until the controller reads it. Only then will the sensor detect a new sun angle. The angle data is returned serially as an IEEE-754 32-bit floating point number, plus status byte, for a total of 40 bits (5 bytes) per angle.

The AC104 Controller/Sun Sensor Interface system can read both sun sensor angles (if present) in just over one second when running the controller at 1000 Hz. Efforts to increase the frequency by a factor of 5 have been hampered by timing synchronization problems between the AC104 and the sun sensor subsystem. Consultation with Wind River is being pursued to identify and correct the timing problem.

To test the interface, a simple closed-loop control system was created using one of the sun sensors as the feedback. This approach involved mounting the sun sensor on a small 9Volt DC motor. The AC104 read the current sun sensor angle, multiplied it by a user selected gain to achieve the desired response, and then output the resulting voltage to an operational power supply which in turn drove the motor to align the sensor with the light source. The power supply was required because the AC104 itself does not have enough source current capability to drive the motor directly. This test was successful. The next planned test is with the sun sensors mounted on the azimuth and elevation axes of the test stand, using the Smartmotor drive system.

FOCUS CONTROL SYSTEM

The design of the focus control system was described in detail in a previous paper[12]. The purpose is to provide a 6-degree-of-freedom platform for focusing the concentrator and locating the focal point at the desired aperture location. Trade studies were performed to compare the parallel robotic structure of a hexapod or Stewart platform (using 6 linear actuators) with a serial robot arm structure (using 6 rotary actuators). The hexapod was chosen based on stiffness and simplicity of the inverse kinematics. Another trade study was performed on the type of linear actuators: a stepper versus a brushless DC servomotor manufactured by Animatics known as the Smartmotor. The stepper actuator has the lowest cost and the drive ELX can be located remotely, but does not have feedback and has potential for missing steps. The Smartmotors feature plug-in EEPROMS to store the program, a built-in encoder, and closed-loop PID control right on board. The Smartmotor was chosen due to its robustness, flexibility, and power, despite its higher cost (about twice the stepper).

Separate funding from the DUS&T Electromagnetic Radiation Control Experiment (EMRCE) program was used to build a laboratory testbed of the system. Six Smartmotor actuators were purchased. These actuators were connected in an RS-232 daisychain to a laptop PC serial port and programmed using the included Smart Motor Interface (SMI) program. The inverse kinematics were linearized and coded into the program. The testbed has been successfully used with a simple optics system to point and focus energy (Figure 14). The operator types in the desired platform displacement and rotation amounts, and the program calculates the required actuator strokes and sends the commands to the actuators.

The system has been further streamlined by integrating it with the AC-104 controller, which uses a graphical interface for adjusting the platform orientation. Now, instead of typing in numbers, the operator uses the mouse to move graphical sliders to adjust the 6 DOF while viewing the quality and location of the focus with a video camera.

It was found that the optics of the double-convex lens and mirror in Fig. 14 do not adequately simulate the angular focus sensitivity of the off-axis

parabolic mirror of the inflatable concentrator. Consequently, the hexapod operator does not gain the proper experience in focusing the system. A small subscale off-axis parabolic mirror was designed, fabricated, and verified (Figure 15). Sensitivity to angular misalignments is high, as expected. It will soon be mounted on the hexapod for more rigorous testing, and will also be used on the integrated ground test stand to simulate the inflatable concentrator.

A 2-foot diameter isogrid ring for the base of the hexapod has been successfully fabricated (Figure 16). A 4-foot diameter isogrid ring for the top of the hexapod has been designed and structurally analyzed, with a predicted out-of-plane deflection of less than 0.2" under the cantilevered load of the 4-by-6 concentrator on the test stand. Fabrication will begin shortly. These rings reduce the weight of the previous hexapod design by about 60%.

ENGINE

The designs of the tungsten engine absorber and molybdenum secondary concentrator are complete. A purchase order is in place with Martin Technologies of Huntsville AL to perform the initial EDM machining of the tungsten blank for the engine absorber. This blank will then be handed off to Plasma Products for finishing using high-density vacuum plasma spray techniques to form the tubular channels of the engine. Axsys Technology of Coleman AL has a purchase order in place to machine the molybdenum secondary concentrator. It is anticipated that these processes will be complete in August 2001.

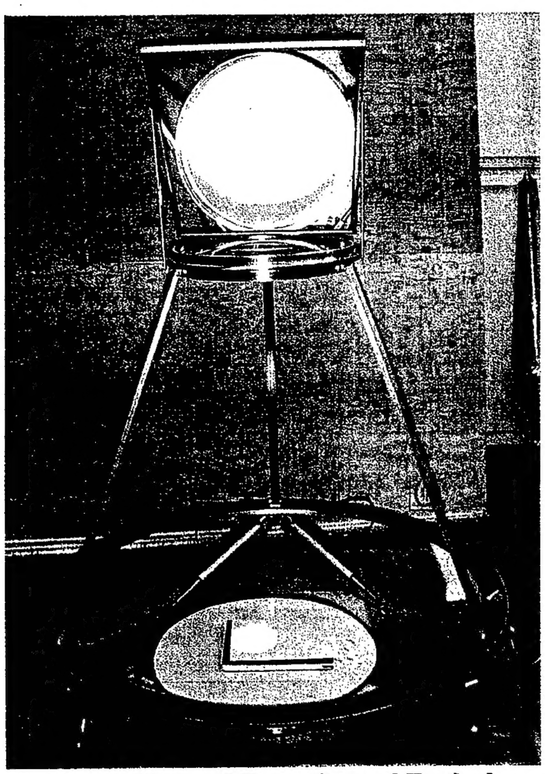

Figure 14. Hexapod Focus Control Testbed

TEST STAND

The design and fabrication drawings of the integrated ground test stand design (Figures 2 and 3) are completed. The vacuum chamber with the quartz window already exists as government-furnished equipment. The large azimuth bearing and the V-roller bearings for the turntable elevation drive have been procured. The other drive system components (timing

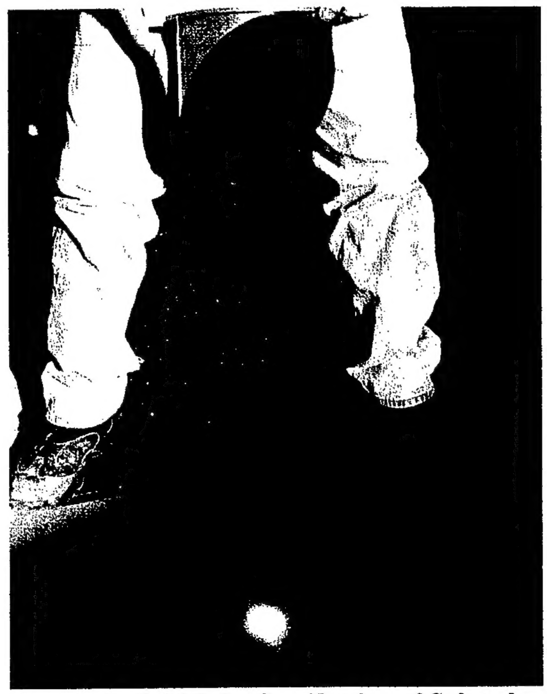

Figure 15. Initial On-Sun Testing of Subscale Mirror

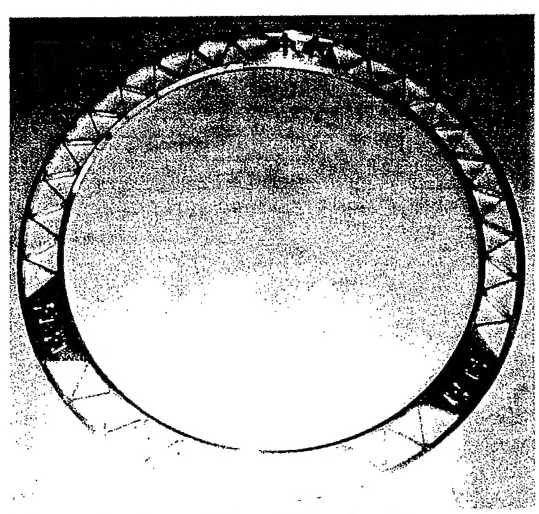

Figure 16. Isogrid Base Ring for Hexapod

belts, Smartmotors, bearings and mounts, etc.) are in the procurement or fabrication process. The sun tracking system and focus control systems will soon be integrated with the test stand. The stand should be complete and ready for checkout testing by Summer 2001.

FUTURE WORK

Two ground tests are planned for the remainder of the program: Integrated Test 6 (IT-6) and the final integrated ground test (IGT).

IT-6 is scheduled for June 2001 in NASA/Glenn's Tank 6 vacuum chamber with a solar simulator powered by multiple halogen lamps (Fig. 17). The objectives of IT-6 are to:

- Demonstrate thermal vacuum operation of a subscale inflatable concentrator and determine power throughput efficiency
- Demonstrate hexapod operation in a simulated space environment
- Thermally characterize a full-scale rigidized strut

The global geometry of the deployed structure will be measured and compared to predicted values generated from structural analysis. Figure 18 shows the subscale concentrator integrated with the hexapod. The hexapod actuator has been successfully operated in a small vacuum chamber under load. The lubrication of all 6 actuators was changed for compatibility with NASA's vacuum chamber requirements.

The final integrated ground test will be a culmination of all hardware built and tested under this effort. The integration hardware will include the

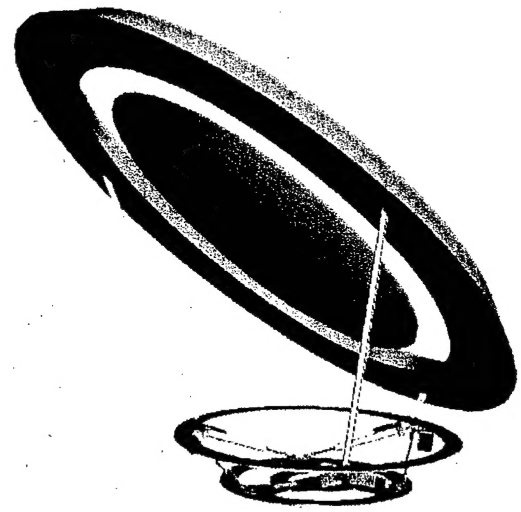

Figure 18. Subscale Concentrator for IT-6

absorber engine, flightscale 4-by-6-meter concentrator, rigidized struts, inflation control system, sun tracking system, and focus control system. The absorber engine will be housed in the vacuum test chamber and receive the concentrated energy through the quartz window. This is necessary to protect the engine from oxidation during on sun testing.

This final test will demonstrate the solar propulsion system with integrated pointing and tracking system in ground based testing.

CONCLUSION

The IHPRPT Solar Thermal Propulsion Demonstration Program has made significant progress

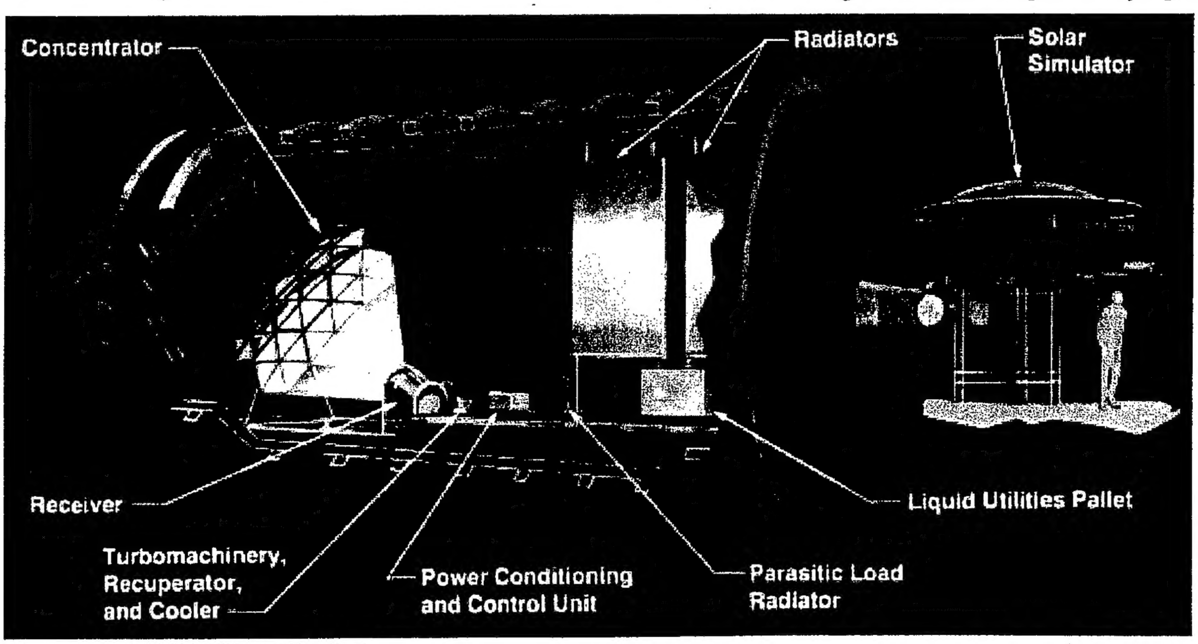

Figure 17. NASA/Glenn Tank 6

towards the first-ever integrated on-sun test of an STP system. The program will soon culminate in a viable ground based test that will demonstrate the technologies necessary for a successful spaceflight experiment.

ACKNOWLEDGMENT

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